

Determining SUSY particle mixing with polarized hadron beams

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While SUSY particles, if they exist at the TeV-scale, will be discovered at the Tevatron or the LHC, the determination of the SUSY-breaking scenario and its free parameters will require additional information, e.g. from a future International Linear Collider. We point out that such information, in particular on SUSY-particle mixing and the associated soft SUSY-breaking parameters, can also be obtained from measurements at existing or future polarized hadron colliders, since the polarization of initial-state quarks, transmitted through weak gauge bosons or squarks, can be strongly correlated with the helicity and gaugino/higgsino mixing of final-state sleptons, squarks, neutralinos and charginos.

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1. Motivation

Weak-scale supersymmetry (SUSY) continues to be one of the best-motivated extensions of the Standard Model (SM) of particle physics, and the search for SUSY particles is one of the top priorities at current high-energy hadron colliders. While SUSY particles, if they exist at the TeV-scale, will be discovered at the Tevatron or the LHC and their masses and some of their properties will ultimately be measured with an accuracy of about 10% in the high-energy and high-luminosity phase of the LHC, it is today unanimously accepted that the determination of the SUSY-breaking scenario as well as its free parameters will require additional and more precise measurements, e.g. from a future International Linear Collider [1]. In this article, we point out that additional information, in particular on SUSY-particle mixing and the associated soft SUSY-breaking parameters, may also be obtained from measurements at existing or future polarized hadron colliders such as RHIC or the Tevatron and LHC after polarization upgrades [2].

2. SUSY particle mixing

Since the two SUSY partners of a chiral lepton or quark doublet are scalars and carry identical quantum numbers, left- and right-handed sleptons $\tilde{l}_{L,R}$ or squarks $\tilde{q}_{L,R}$ can mix into lighter and heavier mass eigenstates $\tilde{l}_{1,2}$ and $\tilde{q}_{1,2}$. The mixing is proportional to the off-diagonal elements of the sfermion mass matrix

$$\mathcal{M}^2 = \begin{pmatrix} m_{LL}^2 + m_f^2 & m_f m_{LR}^* \\ m_f m_{LR} & m_{RR}^2 + m_f^2 \end{pmatrix} \quad (2.1)$$

with

$$m_{LL}^2 = (T_f^3 - e_f \sin^2 \theta_W) m_Z^2 \cos 2\beta + m_{\tilde{L}}^2, \quad (2.2)$$

$$m_{RR}^2 = e_f \sin^2 \theta_W m_Z^2 \cos 2\beta + \begin{cases} m_{\tilde{U}}^2 & \text{for up-type fermions,} \\ m_{\tilde{D}}^2 & \text{for down-type sfermions,} \end{cases} \quad (2.3)$$

$$m_{LR} = A_f - \mu^* \begin{cases} \cot \beta & \text{for up-type sfermions} \\ \tan \beta & \text{for down-type sfermions} \end{cases} \quad (2.4)$$

and thus to the mass of the SM fermion m_f and the soft SUSY-breaking term A_f of the trilinear Higgs-sfermion-sfermion interaction and the off-diagonal Higgs mass parameter μ in the MSSM Lagrangian, divided or multiplied by $\tan \beta = s_\beta / c_\beta = v_u / v_d$, the ratio of the vacuum expectation values $v_{u,d}$ of the two Higgs doublets. This mass matrix is diagonalized by a unitary matrix

$$S = \begin{pmatrix} \cos \theta_{\tilde{f}} & \sin \theta_{\tilde{f}} \\ -\sin \theta_{\tilde{f}} & \cos \theta_{\tilde{f}} \end{pmatrix} \quad \text{with} \quad \begin{pmatrix} \tilde{f}_1 \\ \tilde{f}_2 \end{pmatrix} = S \begin{pmatrix} \tilde{f}_L \\ \tilde{f}_R \end{pmatrix}, \quad (2.5)$$

where the mixing angle $\theta_{\tilde{f}} \in [0; \pi/2]$ is related to the SUSY-breaking masses $m_{\tilde{L}, \tilde{U}, \tilde{D}}$ through

$$\tan 2\theta_{\tilde{f}} = \frac{2m_f m_{LR}}{m_{LL}^2 - m_{RR}^2} \quad (2.6)$$

and the squared mass eigenvalues are given by

$$m_{1,2}^2 = m_f^2 + \frac{1}{2} \left(m_{LL}^2 + m_{RR}^2 \mp \sqrt{(m_{LL}^2 - m_{RR}^2)^2 + 4m_f^2 |m_{LR}|^2} \right). \quad (2.7)$$

If these masses are known, a determination of the sfermion mixing angle will therefore primarily constrain the SUSY and Higgs parameters A_f , μ and $\tan\beta$.

Since the SUSY partners of the neutral and charged electroweak gauge and Higgs bosons are all spin-1/2 fermions, they can also mix to form four neutral and two charged mass eigenstates $\tilde{\chi}_i^0$ and $\tilde{\chi}_i^\pm$. The neutralino mass matrix

$$Y = \begin{pmatrix} M_1 & 0 & -m_Z s_W c_\beta & m_Z s_W s_\beta \\ 0 & M_2 & m_Z c_W c_\beta & -m_Z c_W s_\beta \\ -m_Z s_W c_\beta & m_Z c_W c_\beta & 0 & -\mu \\ m_Z s_W s_\beta & -m_Z c_W s_\beta & -\mu & 0 \end{pmatrix} \quad (2.8)$$

and the chargino mass matrix

$$X = \begin{pmatrix} M_2 & m_W \sqrt{2} s_\beta \\ m_W \sqrt{2} c_\beta & \mu \end{pmatrix} \quad (2.9)$$

depend not only μ and $\tan\beta$, but also on M_1 and M_2 , the SUSY-breaking B -ino and W -ino mass parameters, while m_Z and m_W are the SM Z - and W -boson masses and s_W (c_W) is the sine (cosine) of the electroweak mixing angle θ_W . After electroweak gauge-symmetry breaking and diagonalization of the mass matrix Y with a unitary rotation matrix N , one obtains the four neutralino mass eigenstates. Their decomposition into gaugino and higgsino components is of major importance, in particular for the determination of the nature of dark matter. The application of projection operators leads to relatively compact analytic expressions for the mass eigenvalues. Since X is not symmetric, it must be diagonalized by two unitary matrices U and V . Its squared eigenvalues are

$$m_{\tilde{\chi}_{1,2}^\pm}^2 = \frac{1}{2} \left\{ |M_2|^2 + |\mu|^2 + 2m_W^2 \mp \sqrt{(|M_2|^2 + |\mu|^2 + 2m_W^2)^2 - 4|\mu M_2 - m_W^2 s_{2\beta}|^2} \right\}, \quad (2.10)$$

and the rotation angle $\theta_+ \in [0; \pi]$ of V is uniquely fixed by the two conditions

$$\tan 2\theta_+ = \frac{2\sqrt{2}m_W (M_2^* s_\beta + \mu c_\beta) e^{i\phi_+}}{|M_2|^2 - |\mu|^2 + 2m_W^2 c_{2\beta}} \quad \text{and} \quad (2.11)$$

$$\sin 2\theta_+ = \frac{-2\sqrt{2}m_W (M_2^* s_\beta + \mu c_\beta) e^{i\phi_+}}{\sqrt{(|M_2|^2 - |\mu|^2 + 2m_W^2 c_{2\beta})^2 + 8m_W^2 [(M_2^* s_\beta + \mu c_\beta) e^{i\phi_+}]^2}}. \quad (2.12)$$

If the lightest chargino mass $m_{\tilde{\chi}_1^\pm}$ is known, $|\mu|$ can be determined as a function of M_2 from Eq. (2.10). The anomalous magnetic moment of the muon and rare B -decays both favor $\mu > 0$. In addition, one often assumes not only gauge coupling, but also gaugino mass unification at the GUT scale and therefore $M_1 = 5/3 \tan^2 \theta_W M_2 \simeq 0.5 M_2$ at the electroweak scale, leaving M_2 as the only free parameter determining the gaugino/higgsino decomposition of the neutralinos and charginos.

3. Correlation with beam polarization

Our main observation is that the polarization of initial-state quarks, transmitted through s -channel exchanges of weak bosons or t - and u -channel exchanges of squarks, can be strongly

correlated with the helicity and gaugino/higgsino mixing of final-state sfermions and neutralinos/charginos. While the partonic double-spin asymmetry for s -channel produced sleptons $A_{LL} = -1$ is independent of all SUSY parameters, the single-spin asymmetry $A_L = d\Delta\sigma_L/d\sigma$ with

$$d\Delta\sigma_L = \frac{4\pi\alpha^2}{3s^2} \left[\frac{ut - m_i^2 m_j^2}{s^2} \right] \left[-\frac{e_q e_l (L_l + R_l)(L_q - R_q)}{8x_W(1-x_W)(1-m_Z^2/s)} - \frac{(L_l^2 + R_l^2)(L_q - R_q)(L_q + R_q)}{64x_W^2(1-x_W)^2(1-m_Z^2/s)^2} \right], \quad (3.1)$$

$L_l = S_{j1} S_{i1}^* (2T_l^3 - 2e_l x_W)$, and $R_l = S_{j2} S_{i2}^* (-2e_l x_W)$ is indeed very sensitive to the slepton mixing matrix S and thus the SUSY parameters, in particular since the squared photon contribution is eliminated. It is also easier implemented experimentally, *e.g.* at the Tevatron, since protons are much more easily polarized than antiprotons. Neutralinos and charginos also receive t - and u -channel contributions from squarks, which couple mostly to their gaugino components and render the analysis slightly more complex [2]. However, the single-spin asymmetry remains also in this case the most interesting observable to determine the gaugino/higgsino mixing and, *e.g.*, the W -ino mass parameter M_2 .

4. Experimental prospects

Polarized protons can be created from atomic or optically pumped ion sources with a polarization degree P of up to 87%. During acceleration, this polarization is partially lost in resonance crossings, but this can be avoided by introducing Siberian snakes into the storage ring lattice. In 2009, the RHIC accelerator at BNL has completed a successful pp run with $\sqrt{S} = 500$ GeV and $P \simeq 50\%$ and accumulated an integrated luminosity L of about 50 pb^{-1} , culminating in the first observation of weak bosons in polarized pp collisions [3]. Several more ten-week polarized pp runs are planned, aiming for $P = 65 - 70\%$ and $L = 266 \text{ pb}^{-1}$ in each of the runs [4]. The Tevatron at FNAL is currently operating as an unpolarized $p\bar{p}$ collider at $\sqrt{S} = 1.96$ TeV and has already accumulated more than 4 fb^{-1} in luminosity. A study of proton beam polarization, performed in the mid-1990s, proposes the replacement of some of the dipole magnets to create room for six Siberian snakes, which would lead again to $P = 65 - 70\%$ [5]. The LHC at CERN will be operating as an unpolarized pp collider at $\sqrt{S} = 7$ TeV for two years to reach $L = 1 \text{ fb}^{-1}$, then at $\sqrt{S} = 14$ TeV to reach $L = 100 \text{ fb}^{-1}$. Further upgrades, focusing on even higher luminosity, are currently under discussion. It is interesting to remember that the SSC design had reserved space for Siberian snakes. At the LHC, the required locations would have to be liberated by some of the dipoles.

In Fig. 1 (left) we show the unpolarized hadronic cross sections for pair production of non-mixing tau sleptons at the RHIC, Tevatron, and LHC colliders as a function of their physical mass. Unfortunately, the observation of tau sleptons, as that of any SUSY particles, will be difficult at RHIC, which is the only existing polarized hadron collider. In contrast, tau sleptons will be detectable at the LHC over a large region of the viable SUSY parameter space up to stau masses of about 400 GeV. At the Tevatron, the discovery reach extends considerably beyond the current exclusion limits. For a GMSB model with a light tau slepton, we show the single-spin asymmetry in Fig. 1 (right) as a function of the cosine of the stau mixing angle. The asymmetry is quite large and depends strongly on the stau mixing angle. However, very large values of $\cos\theta_{\tilde{\tau}}$ and stau masses below 52 GeV may already be excluded by LEP [6], while small values of $\cos\theta_{\tilde{\tau}}$ may

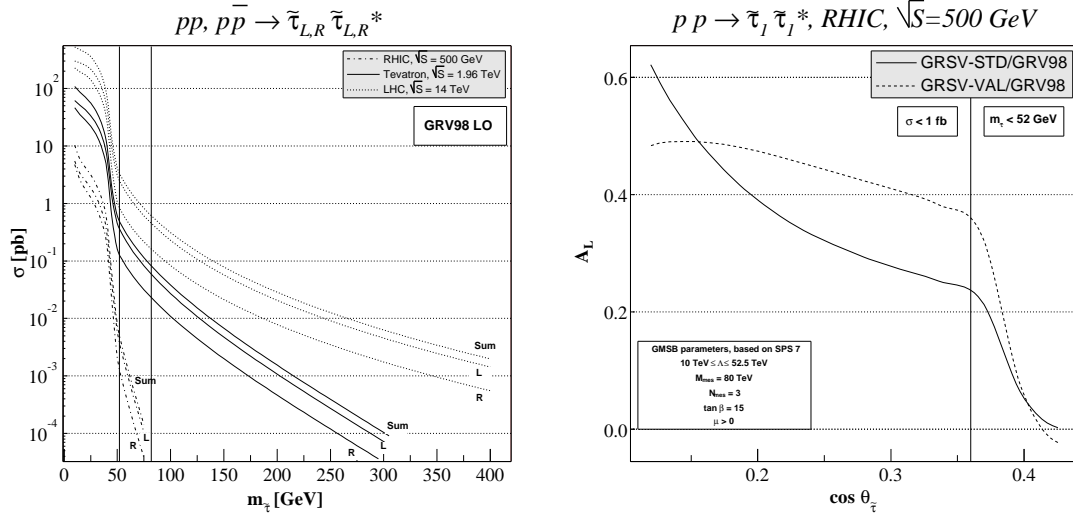


Figure 1: Left: Unpolarized hadronic cross sections for pair production of non-mixing tau sleptons at the RHIC, Tevatron, and LHC colliders as a function of their physical mass. For consistency with the polarized cross sections (see below), GRV98 LO parton densities have been used. The vertical lines indicate two different stau mass limits of 52 and 81.9 GeV [6]. Right: Dependence of the longitudinal single-spin asymmetry A_L on the cosine of the stau mixing angle for $\tilde{\tau}_1$ pair production in a GMSB model at RHIC.

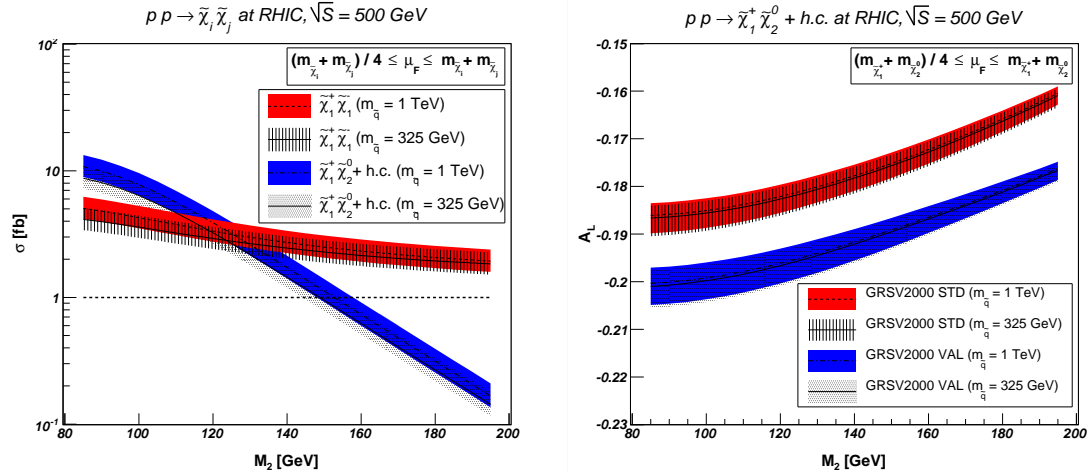


Figure 2: Unpolarized gaugino-pair production cross sections (left) and single-spin asymmetries for chargino-neutralino associated production (right) with $m_{\tilde{\chi}_2^0} \simeq m_{\tilde{\chi}_1^\pm} = 80$ GeV in pp collisions at RHIC and $\sqrt{s} = 500$ GeV.

be inaccessible at RHIC due to its limited luminosity, which is not expected to exceed 1 fb^{-1} . Polarization of the proton beam will also not be perfect, and the calculated asymmetries should be multiplied by the degree of beam polarization $P \simeq 0.7$. The uncertainty introduced by the polarized parton densities increases considerably to the left of the plot, where the stau mass $41 \text{ GeV} \leq m_{\tilde{\tau}} \leq 156 \text{ GeV}$ and the associated values of the parton momentum fractions become large.

In the left part of Fig. 2, we show the total unpolarized cross section for the pair production of the lightest chargino of mass 80 GeV (short-dashed line) and the one for its associated production

with the second-lightest neutralino (dot-dashed line) at the pp collider RHIC. Both cross sections exceed 1 fb in most of the M_2 range shown and depend little on the squark mass, indicating that s -channel gauge-boson exchanges dominate. We vary the unphysical factorization scale μ_F in the traditional way by a factor of two around the average final state mass (shaded bands; for more precise predictions see [7, 8]). Among the bosons exchanged in the s -channel, the W -boson is most sensitive to the polarization of the initial quarks and antiquarks, and consequently the single-spin asymmetry for the associated channel, shown in the right part of Fig. 2, reaches large values of around -20%. As the mass of the neutralino increases and the gaugino fractions of the chargino and neutralino fall up to $M_2 \leq 200$ GeV, the cross section and the absolute value of the asymmetry decrease, too. The uncertainty in the scale variation is with 0.5% considerably smaller than the variation in the asymmetry of 2%, while the uncertainty coming from the polarized parton densities is with 1.5% of almost comparable size. Single-spin asymmetry measurements for associated chargino-neutralino production at the only existing polarized hadron collider RHIC could therefore be used to determine the gaugino and higgsino components of charginos and neutralinos, provided the polarized quark and antiquark densities are slightly better constrained. The single- and double-spin asymmetries for neutralino pairs reach similar sizes as those for the associated channel, since the left- and right-handed couplings of the Z -boson exchanged in the s -channel are also different. However, we do not show them here, since the corresponding cross section is unfortunately too small at RHIC. The variation of the asymmetries would, indeed, be quite dramatic: A_L changes its sign from -20% to +20% for $M_2 \leq 200$ GeV, and A_{LL} falls from -5% to -20%.

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